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From Precambrian to Cenozoic: the manganese odyssey of Morocco

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Morocco is a relevant place to study Mn deposits considering its multistage geodynamic story. In the last decades, several new studies significantly improved our understanding of various genetic types. Three main districts have been mined since the beginning of the 20th century: (i) Ouarzazate (Anti-Atlas), (ii) Bou Arfa (eastern High Atlas) and (iii) Imini-Tasdremt (High Atlas). The first and third are currently mined, accounting for the production of 80,000 tons Mn in 2018 (data from the Ministry of Energy, Mines and Sustainable Development of Morocco). The deposition of Mn spans over four main periods: Neoproterozoic, Jurassic, Upper Cretaceous and Cenozoic.

(i) The Ouarzazate deposits are vein-type and stratiform Mn-Fe orebodies (42-48% Mn) closely associated to Neoproterozoic felsic volcanic and terrigeneous series (Choubert and Faure-Muret, 1973) . It is the largest Mn field in Morocco (>90x60 km). Stratiform orebodies clearly improve the mining potential. The Mn-bearing assemblage includes braunite, cryptomelane, hollandite, hausmannite and pyrolusite in a hematite, goethite, barite, quartz, dolomite and calcite gangue. The formation model implies a polycyclic epithermal and epigenetic Mn accumulation during and at the final stage of the Neoproterozoic volcanic activity at ~580 Ma. Extensional tectonics of the Neoproterozoic Ouarzazate basin would be of primary order in delimiting the number and regional extension of lodes.

(ii) The Bou Arfa Mn deposit is hosted in Sinemurian dolostones, as stratabound, run-type and lenses of Mn orebodies crisscrossed by late veins hosting the high-grade pyrolusite ore (33-82% Mn). Ore formation follows a sedimentary-diagenetic model driven by three dolomitization episodes after the Sinemurian sedimentation, and an epigenetic stage similar to other MVT of the Atlas range (Lafforgue et al., 2021). The concentration of Mn in a narrow area of about 10 km^2 is due to the geometry of the Bou Arfa basin and its position above basement paleohighs acting as a threshold for marine inputs during transgression/regression intervals. The primary manganite-hausmannite ore was transformed into pyrolusite during burial of the Mn-rich sediments.

(iii) The Imini-Tasdremt district is the most economically important of Morocco providing the highest Mn grade (74-92% Mn) due to two stratabound pyrolusite-bearing orebodies hosted in the ~10-20 m thick Cenomanian-Turonian dolostone. A metallurgical third ore (40-48% Mn) occurs in relics of a paleosurface in the uppermost dolostone and is composed by coronadite group minerals (Dekoninck et al, 2016) . Although the pyrolusite ore is restricted to the 25-30 km Imini Mn belt, the metallurgical ore has a larger extension of ~100 km and may extend across the Atlas belt (Dekoninck et al., 2020). New dating of K-Mn oxides (^{40}Ar-^{39}Ar) and goethite (U-Th)/He dating suggest that this geometric distribution is materialized by different formation age: the upper coronadite level is late Cretaceous, whereas the pyrolusite ores are Cenozoic, indicating the importance of local processes. Goethite ages cover a period of ~40 Ma since the Turonian, involving long mineralization processes. The Atlas geodynamics played a significant role in the metallogenesis of these karst-hosted accumulations since late Cretaceous times.

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